Evaluation of Aggregate Stability and Geotechnical Properties of Soils Derived from Dissimilar Shaley Lithological Materials in Selected Locations of Southeastern Nigeria

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ABSTRACT

This research was carried out under three major dissimilar shaley lithological parent materials in selected locations of Southeastern Nigeria. The soil aggregate stability and geotechnical properties were major objects of investigations. Pedons were dug; one in each location of Imo clay shale in Okigwe, Bende-Ameki shale in Uzuakoli and Asata Nkporo shale in Amaike Izzi, all located in Imo, Abia and Ebonyi States of Southeastern Nigeria respectively. These areas lie between Latitude 5o 45' 48" N and Longitude 7o 14' 37" E, Latitude 5o 45' 48" N and Longitude 7o 14' 37" E, Latitude 5o 55' 49" and Longitude 7o 58' 31" E for Okigwe, Uzuakoli and Amaike Izzi respectively. Soil aggregate stability and geotechnical properties were studied from the pedons. From the results, Imo clay shale had the highest average clay fraction (316.5 g kg-1). The mean sand content ranged from 620 - 690.5 g kg-1 and differed significantly (p = 0.05) across the parent materials. The organic Carbon content of the soil varied significantly with means ranging from 8.68 - 14.73 g kg-1. Results of the aggregate stability showed that the Clay flocculation index (CFI) and Clay dispersion ratio (CDI) ranged from 23.10 - 37.59 and 62.2 - 76.27 respectively and tend to have a negative relationship with each other. However, the CFI and CDI of the soils did not differ significantly. The water stable aggregate (WSA) and mean weight diameter (MWD) also did not vary significantly and ranged from 84.25 - 97.20 and 1.59 - 1.72 respectively. The result of the geotechnical properties showed that liquid limit, plastic limit and plasticity index varied significantly with the means ranging from 0.00 - 48.85, 0.00 - 21.68 and 0.00 - 27.18 respectively.

Keywords: *Aggregate stability, Geotechnical characteristics, Parent material, Shaley lithology, Southeastern Nigeria.*

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Highlights of this paper

- Generally, the availability of phosphorus in the soils of the three shaley parent materials was low and could be attributed to the soil reaction which may have influenced the P solubility and availability.
- Soil pH of the studied areas were moderately acidic, soils of southeastern Nigeria are inherently acidic, however, this pH falls within the acceptable limits of 5.0 – 6.5 which is the best pH range for tropical arable soils.
- Results of the aggregate stability showed that the Clay flocculation index (CFI) and Clay dispersion ratio (CDI) tend to have a negative relationship with each other.

1. INTRODUCTION

Soils derived from shaley parent material are most often associated with non-durability [1] resulting to foundation problems and structural failures caused by compositional factors and post depositional processes Holtz and Kovacs [2]; Coduto [3]; Punmia, et al. [4]. Since different shales are composed of different clay mineral species, their silicate structure predisposes them to varying degrees of hydro affinity and volume changes when subjected to cycles of wetting and drying leading to swelling during the rainy season and shrinkage during the dry season. This leads to a number of engineering problems including failures involving cracking, settlement and shear failure of engineering structures founded on them, or when they are used as construction materials.

Shaley soils which are the major components of expansive soils and may be susceptible to swelling and shrinkage which may get to a point wherein it is capable of causing severe damages to road pavements, foundations and infrastructures built on it, and even as impediment to some agricultural practices. The principles of swelling and shrinkage in soils can best be explained and solved by the knowledge and understanding of the mineralogical, chemical and geotechnical composition of the soil and its effect on geotechnical properties of the soil [5].

The geotechnical characteristics of a soil is a function of its structure. According to Karsten, et al. [6] the share strength of a soil is a relevant geotechnical parameter for analyzing and solving the problem of instability in expansive soils, together with other parameters like base saturation, aggregate silt and clay, exchangeable base, clay flocculation, clay dispersion, aggregate stability index etc generally determine the structural stability of the soil.

However, some works have been done on shaley soils by some researchers across the globe [7]. Swelling properties of soils pose significant geotechnical and structural engineering challenges around the world, with costs associated with it running into several billions of money annually. Major aspects that need identification when dealing with shaley soils include: soil geotechnical properties and its correlated aggregate stability. Shaley soils can be found in humid environments where expansive problems occur with soils of high plasticity Index. Several authors Al-Rawas and Goosen [8]; Nelson and Miller [9] and Yilmaz [10] stated that geotechnical properties of shaley soils, with respect to carrying capacity, stress and deformation are highly sensitive to changes in soil moisture regime. Such soils exhibit substantial change in volume on alteration of their moisture content, volume change is however, associated with loss of shear strength as well as deformation. These phenomena can pose a significant hazard to infrastructures. Engineering problems due to shaley soils have been reported Chen and Elliot [11]; Nelson and Miller [9] hence, shaley soils are considered hidden hazards. Considering these findings, there is every need to bring this work down to South-Eastern Nigeria where this shaley soil needs much attention than the soils of other lithological origin. Based on the Unified Soil Classification System (USCS), Ebonyi and Imo shales contain high-plastic inorganic clay, while Ameki shales comprise low medium-plastic inorganic clay. Adesina, et al. [12] also found that shrinkage limit and plasticity index of the soils are positively related suggesting strong influence of the geotechnical properties on their sorption potentials. Overall assessment revealed that the high hydraulic conductivity and swelling potentials of soils of the shaley lithology are not suitable for natural clay liners. Nevertheless, Enugu and Imo shales can further be stabilized chemically to the desired hydraulic conductivity of liners considering other suitable geotechnical properties and their CECs [12]. Imo and Nkporo clay-shale contains appreciable amount of vermiculite, chlorite, glauconite and montmorillonite occurring as a mixed layer which are the major determining mineral for all geotechnical properties of soil while their counterpart Bende Ameki shale has more of Kaolinite as their constituent clay mineral. Adesina, et al. [12] found that Nkporo and Imo clay shale are inorganic clays with high plasticity/shrinkage while Bende Ameki shale is made up of inorganic clay/silt of low–medium plasticity therefore expected to exhibit low shrinkage, and low plasticity. The major objective of this work was to evaluate the aggregate stability and geotechnical characteristics of soils of selected shaley parent materials of south-East Nigeria.

2. MATERIALS AND METHOD

2.1. Study Area

This study was conducted in three different locations in South East Nigeria namely; Uzuakoli in Bende LGA Abia State, Izzi Ebonyi State and Umunna in Okigwe Imo State. These areas lie between latitude 5° 45' 48" N and longitude 7° 14' 37" E (for Uzuakoli in Bende), latitude 5° 55' 49" and longitude 7° 58' 31" E (for Izzi Ebonyi state), latitude 5° 45' 48" N and longitude 7° 14' 37" E (for Okigwe, Imo state). Soils of these areas are generally derived from shale parent material. Uzuakoli soils are derived from Bende Ameki shale, Izzi soils are derived from Nkporo shale while OKigwe soils are derived from Imo clay shale. South-East Nigeria has a humid climate with average annual rainfall of about 1700-3000 mm, average annual temperature range of 24-33°C and relative humidity of 70-80% [13]. The natural vegetation of this area is tropical rainforest. The major occupations of the people are farming, fishing and trading.

2.2. Field Work

Reconnaissance visit was made, through which we obtained useful information concerning the study area. A target sampling guided by geological map was used to locate the sampling points. One profile pit was dug at each of the three locations making it a total of three profile pits. The profile pits were delineated according to generic horizons and they were described using the standard method of FAO [14]. Soil samples were collected from the various horizons for laboratory analyses, undisturbed sample were collected from each of the horizons using core sampler to test for bulk density and water content. For physical and chemical properties, samples were dried at room temperature, crushed and sieved using 2 mm sieve. Uncrushed Samples for aggregate stability were weighed in lumps of 50 g from each of the samples while the samples for geotechnical properties remained uncrushed for the analysis.

3. LABORATORY ANALYSIS

3.1. Physical Properties

Particle size distribution was determined using hydrometer method of Gee and Or [15] using Calgon as dispersing agent. Bulk Density Bulk density was determined in the laboratory using the procedures of Grossman and Reinsch [16]. Moisture Content was determined by Gravimetric method. Total Porosity was determined using the assumed particle density of 2.65 g cm^{-1} [17]. Soil pH was determined in the laboratory using glass electrode pH meter as described by Hendershort, et al. [18]. Organic Carbon was determined by the method of wet oxidation procedure according to Olsen and Somers [19] method. Available Phosphorus was determined by Bray11 method [20]. Exchangeable base cations (Ca, Mg, K, and Na) were extracted with 1 N NH4OAc (pH 7) [21]. Exchangeable calcium and magnesium were determined by EDTA complexio-metric titration while exchangeable potassium and sodium were determined by flame photometry. Total Nitrogen was determined by Kjeldal digestion method [22] using concentrated H_2SO_4 and Sodium phosphate, copper sulphate catalyst mixture. Ammonia in the digest will be placed with 45% NaOH solution and distilled into 4% boric acid and then was determined by titration with 0.05N HCl. Exchangeable Acidity (H^+ and Al^{3+} ion) was determined by titration method [23]. Effective Cation Exchange Capacity (ECEC) was obtained by summation of all exchangeable cation (exchangeable bases + exchangeable acidity).

3.2. Geotechnical Characteristics

Consistency was determined using Moisture-Tension Method by Gadallah [24] The consistency index (CI) was calculated as:

$$CI = \frac{(LL - W)}{(LL - PI)}$$

Where W is the existing water content. Soil at the liquid limit will have a consistency index of 0, while soil at the plastic limit will have a consistency index of 1.

Plastic limit was determined using threading and Rolling method.

Plasticity index is the difference between the liquid limit and the plastic limit (PI = LL-PL). where 0 = Non-plastic, <7 = Slightly plastic, 7-17 = Medium plastic, >17 = Highly plastic

The shear strength was determined using the Mohr Coulomb theory.

Shrinkage Limit was calculated using the formula;

Shrinkage limit

$$(WS) = W - \frac{(V - Vo)}{Wo} X \frac{100}{1}$$

Where w= moisture content of the wet soil

Liquid Limit was determined using Casagrande's liquid limit device

Moisture content was determined by Gravimetric method.

3.3. Aggregate Stability

Kemper and Chepil [25]; Kemper and Rosenau [26] methods were used to determine macro aggregate stability. Water stable aggregate and mean weight diameter (MWD) were the indices used to determine soil macro aggregate. Wet sieving method was carried out using a nest of four (4) sieves with aperture sizes of: 4.75, 2.0, 1.18, and 0.60 mm. Water stable aggregate (WSA) was calculated by;

$$WSA = \frac{weight\ of\ aggregates - weight\ of\ sand}{weight\ of\ sample - weight\ of\ sand} \times \frac{100}{1}$$

$$MWD = \sum^{n} Xi\,Wi$$

Where;

MWD = mean weight diameter (mm).

Wi = proportion of the total sample weight occurring in the corresponding size fraction N = number of size fraction.

Xi = mean diameter of each size fraction.

Micro aggregate was determined using the indices stated by Igwe and Obalum [27]:

Clay Dispersion Index (CDI) was determined using the formula:

Clay Flocculation Index (CFI) was calculated mathematically:

$$\text{CDI} = \frac{\%\text{clay (H20)}}{\text{Clay dispersed}} \text{ X } \frac{100}{1}$$

$$CFI = \frac{\%\ clay\ (dispersed).\ \%\ clay\ (H2O)}{\%\ clay\ dispersed}\ x\ \frac{100}{1}$$

Clay Dispersion Ratio (CDR) was calculated using.

$$\frac{\%Silt + clay\ (H20)}{\%Silt + \ Clay\ (dispersed)}$$

3.4. Statistical Analysis

Data obtained were subjected to analysis of variance (ANOVA). Significant means were separated using least significant difference (LSD) at 5% probability level. Correlation analysis was used to determine the relationship between soil properties [28]. Data analyses were carried out using SPSS version 20.0

4. RESULTS AND DISCUSSION

4.1. Soil Physical Properties

The physical properties of the studied sites are shown in the Figure 1. Results showed that there was significant difference (P = 0.05) in the sand fraction of the soils of the studied area. The highest mean sand fraction (692.5 g kg^{-1}) was recorded in Bende Ameki clay shale while the lowest (620.5 g kg^{-1}) was recorded in Nkporo shale. The silt and clay contents of the areas varied significantly across the sites. Silt fraction ranged between 91.0 g kg^{-1} (Nkporo clay shale) and 46.00 g kg^{-1} (Imo clay shale) while clay fraction ranged between 316.0 g kg^{-1} (Nkporo clay shale) and 226.0 g kg^{-1} (Bende-Ameki clay shale). The bulk density value varied significantly, with the Nkporo clay shale having the highest mean value of 1.57g cm^{-3} while Bende-Ameki clay shale had the lowest mean value of 1.15 g cm^{-3}. There was significant difference in the moisture content and the porosity of the studied area, in Imo clay shale the, highest mean moisture content was found to be 167.5gkg^{-1} while the lowest was found in Nkporo shale recording 79.0 g kg^{-1}. The highest porosity was found at Bende (56.79%) and lowest at Nkporo shale (40.69%).

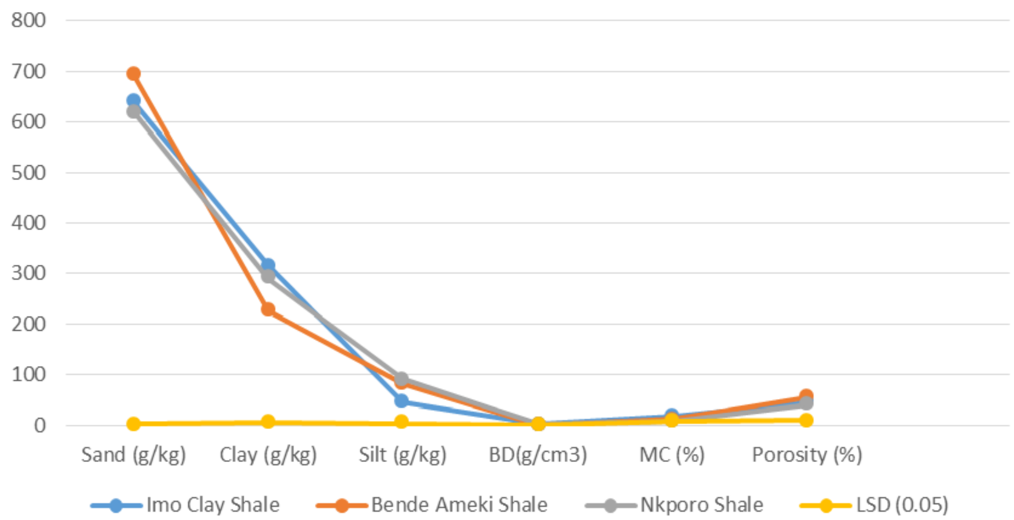

Figure-1. Soil physical properties of the sites.

Note: BD = bulk density, MC = moisture content, LSD = Least significant difference.

4.2. Soil Chemical Properties

The chemical properties of the sites (Imo clay shale, Bende-Ameki clay shale and Nkporo clay shale) are as shown in Figure 2. The study revealed that pH varied significantly (P = 0.05). The pH (KCl) was highest at Nkporo clay shale (5.18) and lowest in the soils of the Imo clay shale (5.09). Generally, the pH of the studied areas were moderately acidic, and this could be because soils of southeastern Nigeria are inherently acidic, however, this pH falls within the acceptable limits of 5.0 – 6.5 which is the best pH range for tropical arable soils [29]. Organic Carbon and total nitrogen contents varied significantly (p = 0.05). Bende Ameki shale had highest mean organic carbon content of 14.73 g kg^{-1} and the highest mean TN of 1.15 g kg^{-1} respectively. According to the rating of Landon [30] the Total Nitrogen of the soils were high. The available phosphorous (P) content of the soil was found to have varied significantly with its highest mean found in Bende Ameki shale group (4.06 mg kg^{-1}) while the lowest was found in Imo clay shale group (2.64 mg kg^{-1}).

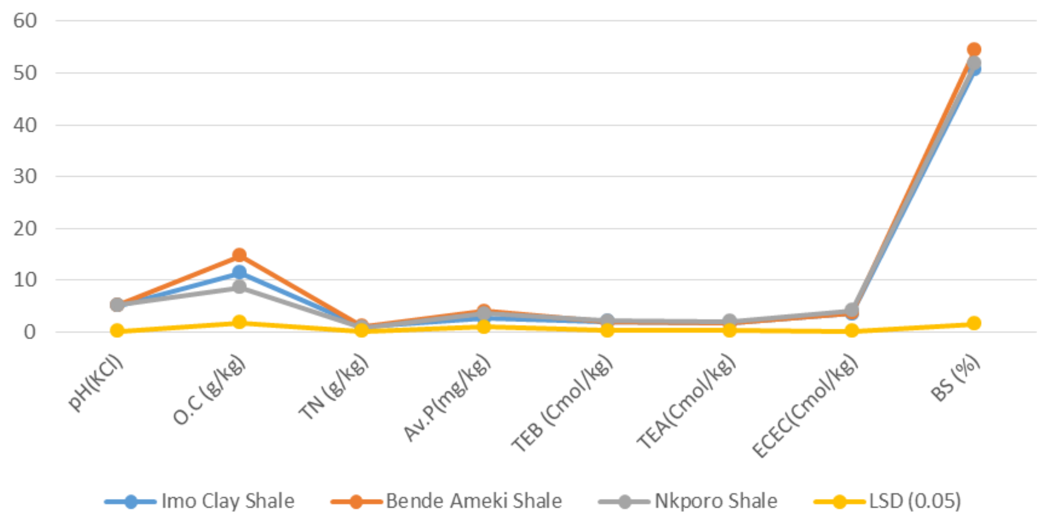

Figure-2. Chemical properties of soils.

Note: O.C = Organic Carbon, TN = Total Nitrogen, Av.P = Available Phosphorus, TEB = Total exchangeable bases, TEA = Total exchangeable acidity, ECEC = Effective cation exchange capacity, BS = Base saturation.

Generally, the availability of phosphorus in the soils of the three shaley parent materials was low and could be attributed to the soil reaction which may have influenced the P solubility and availability; as low (acidity) or high pH (alkalinity) results to P fixation [31]. The Base saturation was moderate, ranging from 50.73 in Imo clay shale to 54.55 % in Bende Ameki shale group respectively.

4.3. Aggregate Stability of the Studied Area

The soil aggregate stability results are shown in Figure 3. From the results, Clay dispersion index (CDI), clay flocculation index (CFI) and clay dispersion ratio (CDR) varied significantly. The CDR, CFI and CDI had mean values ranging from 62.30 -72.27, 37.59 - 0.10 and 0.77 - 0.93 respectively. High CDI and CDR results to low soil aggregate stability. Using CDI and CDR as indices for determining the stability of the soils, soils of the three sites had their stability in the following order; Imo clay shale, Bende-Ameki shale and Nkporo clay shale. The high stability in soils of Imo clay shale could be as a result of presence of high clay content and high organic matter content of the soil. Nadler [32] reported similar result, on the other hand, the higher the CFI, the higher the soil aggregate stability. Considering the CFI of the studied site, the aggregate stability is in the following order, Imo clay shale, Bende clay shale and Nkporo clay shale. This generally explained that the soils of Imo clay shale have the most stable aggregate. According to Igwe, et al. [33] soils with less clay content have low stable aggregate and are most erodible. The reason for low stability recorded in Nkporo shale group could be as a result of low organic carbon content of the soils. Igwe, et al. [33] reported that the flocculation and deflocculation properties of soils are control by organic carbon. The macro aggregate (water stable aggregate and mean weight diameter) varied significantly across the sites. At macro structural level, MWD and WSA>0.5 were used as indices for soil aggregate stability, the higher the value of these indices the greater the stability of the soil. Also, Mbagwu [34] pointed out that higher values of %WSA indicate higher stability. The two indices showed that soils of Nkporo shale were the most stable, followed by the soils of Imo clay shale and lastly, soils of Bende Ameki shale group. Significantly higher stable aggregate recorded in Nkporo clay shale soils is a reflection of the micro aggregate, texture and organic carbon results. Aggregate stability of soils is influenced by quality and quantity of organic matter, soil texture and cation content Adesodun, et al. [35]; Boix-Fayos, et al. [36]; Levy and Torrento [37].

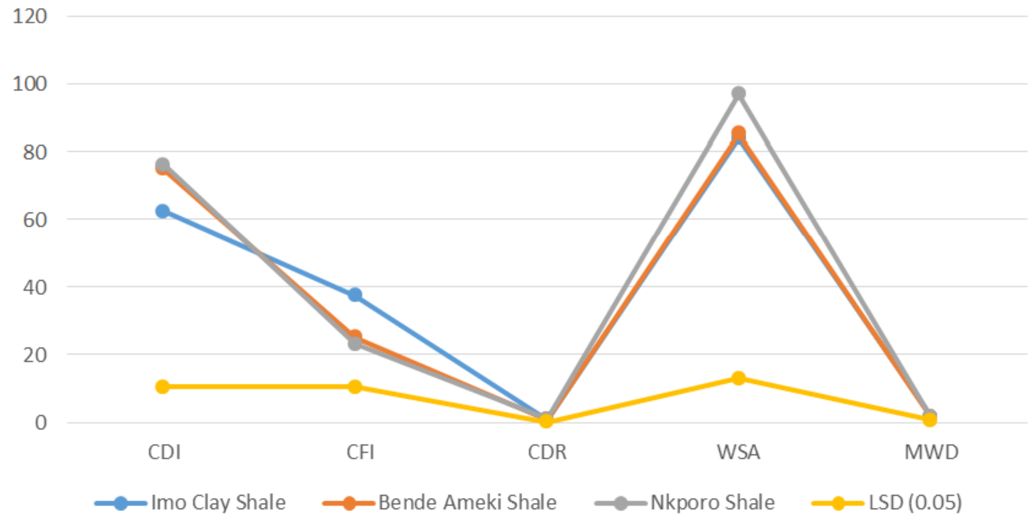

Figure-3. Aggregate stability indices of the soil.

Note: CDI = Clay dispersion index, CFI = clay flocculation index, WSA = Water stable aggregate, MWD = Mean weight diameter.

4.4. Geotechnical Properties of Soil

The geotechnical properties of the studied areas are shown in the Figure 4. The results showed that the atterberg limit (liquid limit, plastic limit, plasticity index) varied significantly. Liquid limit has the highest mean of 48.85 in Imo clay shale and the lowest mean of 0.00 in Bende clay shale. Plastic limit had its highest mean value at Imo clay shale (21.68) and had 0.00 as its lowest mean at Bende. 27.18 was the highest mean value of plasticity index, recorded at Imo clay shale with its lowest mean value of 0.00 at Bende.

It was discovered that Bende had zero mean value in the atterberg limit, indicating that Bende soils are not plastic and therefore comformed with the finding of Adesina, et al. [12] who stated that Nkporo clay shale and Imo clay shale are inorganic clays with high plasticity/shrinkage while Ameki shale is made up of inorganic clay/silt of low-medium plasticity therefore expected to exhibity low shrikage, and low plasticity. The zero mean value obtained in Bende Ameki soils could be attributed to the type and quantity of clay present in them. Clay content determines the amount of surface area that is available for water adsorption. Generally, the quality and quantity of clay affect plasticity of any given soil. Clay type influences plasticity because of the effect of the ability of clay surfaces to absorb and orient water molecules.

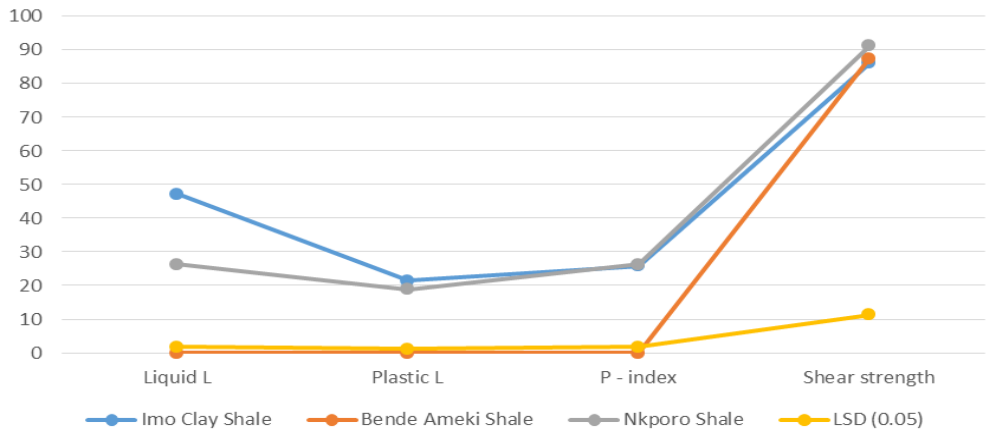

Figure-4. Geotechnical properties of the studied area.

4.5. Relationship between Geotechnical Properties and Other Soil Properties

The result of the correlation between geotechnical properties and soil physico-chemical properties of the studied area are shown in Table 1. Result showed that plastic limit correlated positively with bulk density (r = 0.731), available phosphorus (r = 0.989), Clay (r = 0.861), but correlated negatively with base saturation (r = -0.7528), Organic Carbon (r = -0.6146) Sand (r = -0.7835) and total Nitrogen (r = -0.5507). The positive correlation between plastic limit and BD explained the idea that as the soil particle come together, they increase plastic behavior of the soil. Soil particles in a distant apart cannot make a thread or become plastic. This is in line with the findings of Hakansson and Voorhees [38] and Imhoff, et al. [39]. Also, as the clay content of the soil increases, the soil tends to have more plastic behavior. For a soil to have plastic behaviour, the sand content must be lesser than the clay content, this was proven by the negative significant correlation observed between the plastic limit and sand content of the soil. The plasticity index correlated positively with, bulk density (r = 0.6439) and Clay (r = 0.8463) while sand (r = -0.7543), organic carbon (r = -0.6338) and total nitrogen (r = -0.5631) correlated negatively with plasticity index.

Table-1. Relationship between geotechnical properties and soil properties.

Soil property	Plastic L	Liquid L	P INDEX	Shear strength
AP	-0.3766	-0.4174	-0.3451	0.0631
Al	0.5976*	0.3125	0.6439*	0.2024
BD	0.7311**	0.5812*	0.7393**	0.0618
BS	-0.7528**	-0.7073**	-0.7543**	0.1492
Ca	0.0477	-0.1537	0.0816	0.2427
ECEC	0.0955	-0.1001	0.1479	0.1275
H	-0.3252	-0.075	-0.2969	-0.0256
K	-0.0603	-0.1303	-0.0515	0.0085
MC%	-0.1344	-0.1158	-0.2087	0.0112
Mg	-0.2971	-0.3136	-0.2732	0.0156
Na	0.4966	0.2200	0.5200*	0.1677
OC	-0.6146*	-0.3993	-0.6338*	-0.1373
P	0.9893**	0.896**	1.0000**	-0.0557
PH_H2O	-0.0966	-0.2823	-0.0657	0.2663
Sand	-0.7835**	-0.6335*	-0.7806**	-0.0967
TAE	0.1886	-0.0271	0.2458	0.1738
TEB	-0.0032	-0.0709	0.0085	0.3108
TN	-0.5507*	-0.4172	-0.5631*	-0.057
Clay	0.8611**	0.7602**	0.8463**	-0.044
porosity	-0.7094**	-0.5513*	-0.7262**	-0.0442

Note: *and ** = sig at 0.05 and 0.01 probability levels respectively.
BD = bulk density, MC = moisture content, O.C = Organic Carbon, TN = Total Nitrogen, Av.P = Available Phosphorus, TEB = Total exchangeable bases, TEA = Total exchangeable acidity, ECEC = Effective cation exchange capacity, BS = Base saturation.

4.6. Relationship between Aggregate Stability and Soil Properties

Table 2 represents the relationship between aggregate stability and physico-chemical properties of soils Results showed that CDR correlated positively with aluminum (r = 0.5466), calcium (r = 0.5783), ECEC (r = 0.5046), Sodium (r = 0.5028). WSA correlated positively with aluminum (r = 0.6842), Phosphorus (r = 0.5114), but negatively with base saturation (r = - 0.5474).

Table-2. Relationship between aggregate stability of soil and soil properties.

Soil properties	CDI	CFI	CDR	WSA	MWD
AP	0.106	-0.0634	0.2451	-0.2542	-0.2531
Al	0.3557	-0.3726	0.5466*	0.6842*	0.3448
BD	0.1292	-0.1021	0.3141	0.4937	0.1925
BS	-0.1016	0.1226	-0.203	-0.5474*	-0.4534
Ca	0.1707	-0.2119	0.5783*	0.3263	0.400
ECEC	0.1386	-0.1006	0.5046*	0.1964	-0.2583
H	0.0314	-0.0713	-0.0431	-0.2181	0.002
K	-0.3129	0.3398	0.1056	0.0218	0.5778*
MC	-0.2963	0.3028	-0.3503	-0.0851	0.2340
Mg	0.0126	-0.0094	0.0446	-0.2005	-0.2783
Na	0.1182	-0.1034	0.5028*	0.4369	0.1887
OC	-0.2335	0.2349	-0.271	-0.5454*	-0.469
P	-0.0414	0.071	0.3886	0.5114*	0.3979
pH(H_2O)	0.4627	-0.4803	0.233	0.4001	0.0903
Sand	-0.2793	0.2655	-0.1524	-0.4674	-0.4882
TAE	0.0939	-0.0874	0.4041	0.4543	-0.2023
TEB	-0.0183	0.0617	0.3994	-0.1099	-0.2897
TN	-0.1901	0.2076	-0.1767	-0.5135*	-0.4309
Clay	-0.1755	0.2031	0.2139	0.4251	0.4504
Porosity	-0.1400	0.0926	-0.3507	-0.4807	-0.1936

Note: *and ** = sig at 0.05 and 0.01 probability levels respectively.
CDI = Clay dispersion index, CFI = clay flocculation index, WSA = Water stable aggregate, MWD = Mean weight diameter.

5. CONCLUSION

The study evaluated the aggregate stability and geotechnical properties of soils of Imo clay shale, Bende Ameki clay shale and Nkporo clay shale of Southeastern Nigeria. From the results, the clay and sand content differed significantly across the sites. Nkporo shale had the highest average clay fraction (333.5g kg^{-1}). Also, the organic carbon and total nitrogen content of soils varied significantly (p = 0.05). The WSA and MWD varied significantly with mean value ranged between 59.63 and 92.83; 1.32 and 1.94 respectively. The result of the geotechnical properties showed that liquid limit and plastic limit varied significantly with the mean value ranging from 0.00 - 48.85 and 0.00 - 21.68 respectively. Plasticity index differed from each other while the shear strength of the soil did not differ significantly from each other. From the result, higher stable aggregate was observed in soils of Imo clay shale. Also PL of the soils of Imo clay shale was the highest with the soils of Imo clay shale having the highest liquid limit. Also Plastic index was higher in soils of Imo clay shale while soils of Nkporo clay shale had the highest shear strength.

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